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SETUP AND DESIGN OF GREEN ANALYTICAL LAB: REFINING ANALYTICS WITH NATURE IN MIND

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ABSTRACT

Background: In recent years, the growing concern for environmental sustainability has extended into all sectors of science, including analytical chemistry. In response to the need for eco-friendly scientific practices, the concept of Green Analytical Chemistry (GAC) has gained significant prominence. One of the most impactful developments under GAC is the establishment of Green Analytical Laboratories (Green Labs), advanced facilities designed to perform analytical procedures while minimizing environmental impact. These labs are committed not only to delivering accurate and reliable analytical data but also to do so in a way that is safe, sustainable, and resource-efficient.[1] By transforming conventional laboratories into sustainable research environments, Green Analytical Laboratories represent a vital step toward achieving the global objective of sustainable scientific innovation. Their adoption is especially crucial in fields such as pharmaceutical analysis, where the demand for precise analytical data is high, and environmental considerations are increasingly being prioritized.

KEYWORDS: Green analytical laboratory, equipment selection, waste management.

INTRODUCTION

"A Green Analytical Lab is a modern scientific workspace that combines advanced analytical techniques with eco friendly practices, aiming to minimize environmental impact by reducing hazardous waste, conserving resources and promoting sustainability - without comprising the accuracy, reliability or efficacy of analytical results"[2] One of the most significant advancements driven by GAC is the establishment of **Green Analytical Laboratories (Green Labs)** — facilities designed to implement environmentally responsible practices throughout the analytical workflow. These laboratories aim to integrate sustainability into every stage of analysis, from sample preparation and instrument operation to waste management and energy conservation.

Table 1: Comparison of green analytical lab and conventional analytical lab.

Aspects	Conventional analytical methods	Green analytical method(GAM)
Solvent Use	High consumption of toxic and volatile organic solvents (e.g., acetonitrile, methanol, chloroform).	Use of safer, less toxic, or bio-based solvents like ethanol, water, or **NADES** (Natural Deep Eutectic Solvents); often solvent-free.
Sample Volume	Requires large sample volumes (mL to g scale).	Miniaturized systems use micro- or nano-liter volumes, reducing resource consumption.
Instrumentation	Large, energy-intensive equipment like HPLC, GC with flame detectors, etc.	Low-power or portable devices like microfluidics, lab-on-a-chip, direct spectroscopy, and electrochemical sensors.
Waste Generation	Generates large volumes of	Designed to reduce or eliminate waste; waste is often

	chemical and plastic waste.	biodegradable or recyclable.
Example Techniques	HPLC with UV, GC-MS, Spectrophotometry with organic solvents.	Capillary electrophoresis, Direct solid sampling, Microextraction, Supercritical fluid extraction, UHPLC, Electrochemical sensors, FTIR-ATR.
Cost	Expensive due to solvents, waste disposal, and energy use.	Long-term cost-saving via reduced resource use, waste, and energy.

Specialized green lab accreditation bodies

1) My Green Lab Certification **(**USA-based, globally accepted).[2]

2) LEADERSHIP IN ENERGY AND ENVIRONMENTAL DESIGN (LEED) Certification.[3]

Procedure to obtain my green lab certificate

Table 2: Precedure for green lab certification.

Step 1	Submit application Via **Visit** https://www.mygreenlab.org
Step 2	Kick-Off an Orientation Meeting with Lab heads.
Step 3	Pre-Assessment Survey (Behavioral & Operational Survey) (10–20 min per person) The survey assesses practices in 14 key areas, including: . Waste Management, Chemical Use, Cold Storage, Fume Hoods, Energy Usage, Water Usage, Procurement, Green Chemistry Practices, Management, Equipment, Sterilization/Autoclaves, Behavior Change, Community Engagement
Step 4	Receive Pre-Assessment Score and Recommendations My Green Lab provides a pre-assessment report:Current sustainability level, Scorecard across all 14 categories, Specific improvement suggestions.
Step 5	Implementation of Sustainable Lab Practices(8–12 weeks) Adjusting cold storage temperatures from -80°C to -70°C, Turning off equipment when not in use (using timers or smart plugs), Closing fume hood sashes when unattended, Purchasing eco-labeled products, Switching to LED lighting, Reducing use of single-use plastics
Step 6	Post-Assessment Survey After implementation, lab members retake the same online survey.
Step 7	Final Analysis and Scoring Evaluates your final survey responses. Each of the 14 categories is scored from 0 to 10.Total possible score: 140 Certification Levels: Level — Score Range Bronze — 50 to 69 Silver — 70 to 89 Gold — 90 to 119 Platinum — 120 to 140
Step 8	Certification Issuance and Recognition Validity: The certification is valid for 2 years

Basic steps in setting up of GAL

Sustainable lab design

(a) Purchase Energy and Water-Efficient Equipment: Eg-vortexes, drying ovens, and water baths to bigger items like refrigerators and freezers. Benchtop NMR spectrometers **(**consume up to 80% less energy than traditional NMR systems), Solar-powered devices (like compact UV-Vis spectrophotometers from Ocean Insight), Energy-efficient cold storage (Stirling Ultracold consume around 40% less energy than conventional -80°C freezers.)

(b) Enhance the Energy Efficiency of Fume Hoods.

(c) Rethink Water Purification Systems.

(d) Install Low-Flow Aerators in Lab Sinks.

(e) Eliminate Single-Pass Cooling Systems.

(f) Optimize Temperature and Ventilation Controls.

Equipment selection

(a)UHPLC (Ultra High Performance Liquid Chromatography): utilizes smaller particle sizes in the column and higher pressures to achieve faster analysis times, improved resolution, and increased sensitivity.

(b) Solid Phase Microextraction (SPME): solvent-free sample preparation technique, SPME is known for its simplicity, speed, and ability to perform sampling, extraction, and pre-concentration in a single step.

(c)Supercritical fluid extraction (SFE): Commonly Used Supercritical Fluid: Carbon Dioxide ($CO_{2)}$, Co-solvents (ethanol or methanol)

(d) Waste-Reducing Lab Tools: (Eg-Biotage, reclaim and purify commonly used solvents like acetone and hexane.

Waste management

Solvent waste management

1. Solvent-Free/Minimized Extraction

Water-Based HPLC

Green Mass Spectrometry in Environmental Analysis: Ambient ionization techniques, such as desorption electrospray ionization (DESI) and direct analysis in real time (DART)

Direct Analysis Methods: Direct analysis in real-time (DART) mass spectrometry is a technique that allows for the direct analysis of samples in their native state.

Automated Systems:
E.g.
(I) UHPLC-MS/MS assay using environment friendly organic solvents: A green approach for fast determination of quetiapine in rat plasma[4]
(II) Replacement of Acetonitrile with Methanol and Ethanol.[5]
(III) Green Pharmaceutical analysis of Rifaximin in dosage form by HPLC Coupled with MS(HPLC-MS) and microbiological turbidimetry.[6]

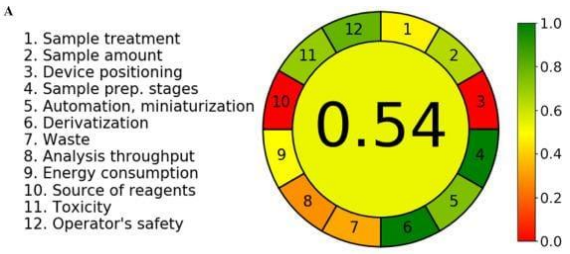
Green solvent
Supercritical Fluids, Deep Eutectic Solvents (DES), Bio-Based Solvents, Alcohols and Glycerol, Organic Carbonates, Fluorous Solvents, Use catalyst not stoichiometric reagent, Green chromatograpic technique.

How to dispose a specific solvent
Ether- Six-month-old ether stored in metal cans should be transferred to plastic coated or glass bottles, and also, it should be diluted with water before its disposal. However, if the metal can is expired, it should not be opened or used again, and it Should be disposed of as per the methods given in its Safety Data Sheet.

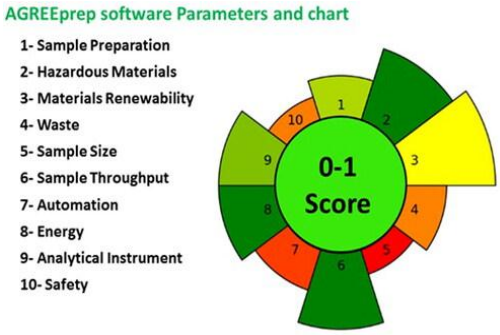
Treatment of solvent waste
(I). Fractional Distillation.
(II) Steam Stripping.
(III) Wet Oxidation.

Green metrics and green analytical application
Green metrics help us to evaluate how environment friendly the analytical procedure.

Analytical GREEnness metric (AGREE)
- Introduction and Structure: Introduced in 2020 by Pena-Pereira et al., AGREE is a free tool whose evaluation criteria are based on twelve principles of green analytical chemistry. Its results are presented as a pictogram with 12 sections (representing principles) and a central circle for the final score (0 to 1), using red, yellow, and green colors.
- Results, Interpretation & Advantages: A score of 0 indicates unsatisfactory, and 1 indicates satisfactory. Key advantages of AGREE include its comprehensiveness (covering all green analytical chemistry principles), flexibility (allowing modifications), ease of analysis of positive/negative aspects, provision of both qualitative and quantitative results, and user-friendly software with fast results.
- Main Disadvantage & Popularity: The most significant disadvantage is that the weighing for each section is not specified. Despite this, AGREE is one of the most widely used tools for greenness assessment.[7,8]



Analytical GREEnness metric for sample preparation (AGREEprep)
- Focus and Structure: Proposed in 2022 by Wojnowski et al. as an improvement to the AGREE tool, AGREEprep specifically focuses on sample preparation. Unlike AGREE, its pictogram has 10 sections surrounding a central circle, with the lengths of these sections varying according to their weights.
- Key Advantages: AGREEprep's interfaces and score scale are similar to AGREE, making them easy to understand. Its significant advantages include its ability to evaluate sample preparation steps, assess unconventional procedures, and allow for the determination of weights for different parameters.[7,9]



NIOSH Hierarchy of Controls
Most Effective to Least Effective: Elimination (Physically remove the hazard), Substitution (Replace with a less hazardous alternative), Engineering Controls (Isolate people from the hazard (e.g., fume hoods)), Administrative Controls (Change how people work (e.g., shift rotations), PPE (Use protective equipment as a last resort)[10,11]

Documentation practices in GAL
(I)LIMS(Laboratory Information Management system).[12]
(II) Real-Time Inventory Tracking.[13]
(III) Cost savings and waste reduction.
(IV) Audit Trails.

DISCUSSION
In summary green analytical laboratory helps in,
1. Environmental Sustainability-Reduced chemical waste, Lower carbon footprint Sustainable resource use.

2. Economic and Operational Efficiency-Cost savings, Miniaturized techniques, Lower energy and water use.
3. Regulatory and Industry Compliance-Support for ESG and SDGs: Environmental, Social, and Governance (ESG) standards and Sustainable Development Goals (SDGs), Easier regulatory approvals.
4. Enhanced Lab Safety and Worker Health-Reduced exposure to toxic chemicals, Better air quality.
5. Scientific Innovation and Technological Advancement-Adoption of modern techniques.(Non-destructive testing methods, Development of green solvents: e.g., NADES (Natural Deep Eutectic Solvents), ionic liquids, water-based systems.)
6. Social and Educational Impact-Promotes eco-conscious education, Better public image(progressive and socially responsible)
7. Improved Analytical Performance-Faster and simpler methods, Higher selectivity and sensitivity.

CONCLUSION

- Green methods (e.g., SPME, LPME) enable real-time analysis, with less waste, fewer chemicals, and lower energy use.[14]
- Compared to traditional techniques (chromatography, spectrophotometry), green methods offer faster results and long-term cost savings.
- Challenges: regulatory acceptance, standardization, scalability, and some technical limits.
- Minimize environmental footprint, improves operational efficiency, culture of sustainability with in scientific community.
- Promotes environmental responsibility among researchers and students.
- Green labs turn every analysis into an act of environmental care and scientific excellence.

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